Nature and Properties of Earthquake Energy and Waves and their Contribution to Liquefaction Aspects at Adani Port During 2001 Bhuj Earth Quake

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NATURE AND PROPERTIES OF EARTHQUAKE ENERGY AND WAVES AND THEIR CONTRIBUTION TO LIQUEFACTION ASPECTS AT ADANI PORT DURING 2001 BHUJ EARTH QUAKE

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ABSTRACT

During Bhuj earthquake of 2001, certain distinct phenomenon in coastal saturated granular deposits were observed causing extensive distress to Adani Port facilities. An attempt is made to analyse the root cause by examining nature and properties of earthquake energy, geometry of earth and the origin of energy and propagation of waves, including excess pore water pressure contributed by P-wave. Although pile raft system were less damaged due to liquefaction, the tests showed extensive loss of load capacity. These aspects are presented in this paper.

1 INTRODUCTION

Adani Port is located on coastal sedimentary granular deposits and is at a distance of 70 km from Bhuj earthquake epicenter of January 2001. Considerable damage took place to port facilities such as, jetties, piled foundations, rafts storage structures and railway lines etc. during earthquake

Certain distinct phenomena in regions having granular sedimentary soil deposits were observed, such as (i) appearance of 2 m to 9 m high jets immediately after earth quake and subsiding gradually during a period of 1 to 2 months and gets springing out from sand boil holes carrying with them sand particles of size varying from 1 mm to 2 mm, (ii) heaving and subsidence of ground accompanied by tension cracks, (iii) rise in ground water table upto ground level accompanied by oozing of water at the surface or formation of a jet, (iv) rise in temperature of water, (v) consistent damage to structures in a corridor, (vi) direction dependent damage, where in a jetty experienced damage but the one perpendicular to it did not, and (vii) buried river channels reappearing at the surface etc. Analysis was conducted based on effective stress approach coupled with S-wave approach put forward by Bolton Seed (1971, Terzaghi, 1965; Prakash, 1981, Katti et.al, 2000, Katti, Dinesh, 2002), it is observed that the excess pore water pressure observed in the field were far in excess of the estimated quantities.

Earth quake as such is an energy based phenomenon arising from the constituents of the earth and its geometry and origin, (Polyakov, 1985, Vogel, 1997). This energy released at some weak points in the earth crust called epicenter propagates in wave forms in all directions, through matter in the body of the earth and earth crust. The intensity of earth quake attenuates with distance from the epicenter.

Thus, to evolve rational measures to prevent the damages to structures due to earth quake on these deposits, it is necessary to examine the role played by the properties of different elements falling in the field of geology, physical - chemistry of matter including properties of waves and engineering of structures resting on such deposits etc. in an integrated way. Soil is conceived as consisting of unconsolidated mineral mass in particle form, air, water organic matter and any other substances. All these are nothing but matter consisting of electrons, protons, neutrons and subatomic particles in different numbers arranged in different geometrical formations and electrons rotate relative to other particles and are held to each other with different degree of bonding. They may exist in solid, liquid or gaseous state and some of these matters as individual or while interacting with each other generate, heat, electricity, light or mechanical energy etc. The matter as such is conceived to contain, (i) mass, (ii) universal gravitational attractive force and (iii) different types of energies with properties to convert from one to another during interaction maintaining conservation of energy principles. Energy in a general form is expressed as equivalent of measurable mechanical energy having dimension, ML^2 T^{--2}. However, different types of energies exhibit different properties, propagate through different media consisting of different matter at different rate and sharing with other matter some of their properties and cause instability to existing matter including change in state (Moore, 1955, Resnic, 1992, Katti, 2000).

Newton put forward principles based on his fundamental observation, force, f α a, the acceleration and m is a proportionality constant and it turns out to be measure of mass. However, during early periods energy was considered to be an independent entity that moved matter from place to place.

However, recent discoveries by Einstein ($E=c^2$ m) Plank ($E=h\upsilon$), Bhor, Broglie and Shrodinger showed that all material particles must possess wave like properties. **Radiation exhibited both corpuscular and undulatory aspects. Mass and energy are not two distinct entities. But they are two different names for the same thing.** Thus, to deal with mechanics of waves which possess, mass-energy and propagate in wave form, Shrodinger, based on concept of packets of energy called quantas put forward his famous equation to develop wave / quantum mechanics.

$\frac{d^2\psi}{dx^2} + \frac{8\psi^2 m}{h^2}(E-U)\psi = 0$ for one dimensional case and $\nabla^2\psi + \frac{8\pi^2 m}{h^2}(E-U)\psi = 0$. This is derived from space time equation.

$\frac{\delta^2\phi}{\delta x^2} = \frac{1}{\mu^2} \cdot \frac{\delta^2\phi}{\delta t^2}$ by substituting $\phi = \psi(x).\sin 2\pi \mu t$

wherein, ϕ = displacement; μ = frequency; h = Plank's constant (0.62×10^{-27} erg sec); t = time; E = total energy; U = potential energy and m = mass.

(For more details refer to physical chemistry book by J. Moor, 1955 or any other standard textbook on wave / quantum mechanics).

In civil engineering one deals with saturated granular media consisting of matter containing granular particles and water or water containing soluble salts etc., (Terzaghi, 1965, Seed, 1971, Prakash, 1981, Katti, 2001) when the energy in the form of waves passes through these matters interaction takes place between solid particles and water and during this process physical state of particles and water alters with respect to displacement, pressure including change in state of matter, (pressure increase in pore water is termed as excess pore water pressure) and displacement in solid particles may further contribute to excess pore water pressure. This excess pore water pressure when exceeds effective stress the state of soil water system is considered as having exhibiting liquefaction phenomenon. Thus, the structures founded on such deposits experience loss of bearing capacity, additional force components and vibration etc.

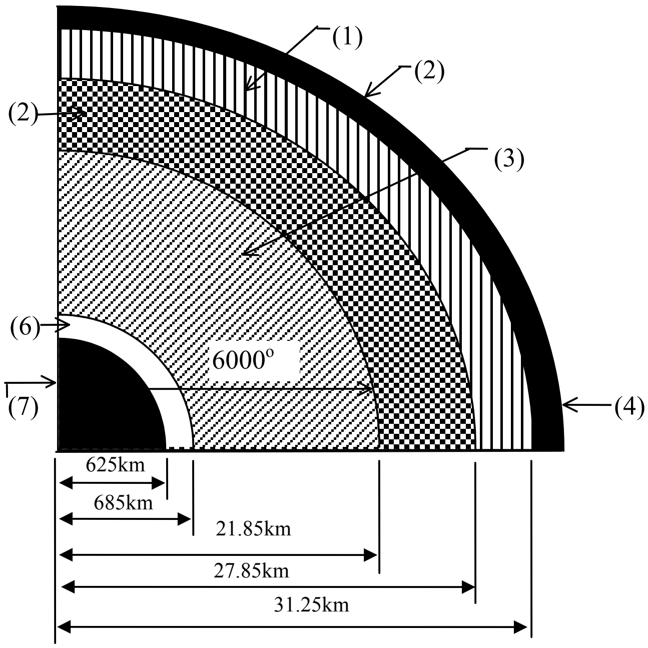
From above it is clear that energy and mass propagate in different types of wave form with different frequency, wavelength, amplitude and velocity. Some of them considered significant for engineering analysis, some may be transverse and some may be longitudinal. In engineering transverse waves, which are called shear or S-waves obtained from seismographs are considered significant for engineering analysis. However, to account for high excess pore water development as observed, there is a need to examine the nature and properties of longitudinal waves called as P-waves on pore water pressure developments.

As the earthquake is a phenomenon resulting from the energies released from the interior of the earth an understanding of the nature and properties of earth and constituents of interior of earth would be helpful in understanding distinct phenomenon observed during earthquake as mentioned above.

An understanding of wave propagation on the spherical earth surface and below may be of importance in evolving energy barriers to protect structures in a group. Although some pile supported rafts appear intact but surrounding soil which has gone into liquefaction appears to have caused weakening of the pile integrity. These aspects are briefly described in this paper.

2 NATURE AND PROPERTIES OF SPHERICAL EARTH, ITS CONSTITUENT ELEMENTS RESPONSIBLE FOR GENERATION OF EARTH QUAKE ENERGY

Earth is a part of solar system which is in dynamic equilibrium and is subjected to different types of forces and rotations in an orderly fashion. It is an oblong spherical body rotating around N-S axis. Electro-magnetic field passes between North and South Poles. A section of earth is shown in Figure 1. The mass of earth constitutes different minerals such as matter containing atoms arranged in different crystallographic array. The minerals in the earth mass may be radio active minerals generating temperature as high as 6000^{o}F accompanied by pressure around 4000 kg/cm^2 (Polyakov, 1983, Vogel, 1997, Hooft, 2002). Thus, the matter may be in liquid, gaseous or solid state. The matter may interact with each other and release mass energy in the form of mechanical energy, thermal energy light energy, electrical energy or nuclear energy separately or in combination. Earth crust is around 33 km thick and due to arching action, hoop stress and gravitational forces, these forces balance the forces arising from interior of earth mass. There exists tension, compression in the crust and results into formation of mountains, oceans and valleys on the earth surface. Earth crust which is supposed to be acted upon by tectonics, plate tectonics and convection currents etc. is producing weak points in the form of faults, joints etc. having high elastic strain energy (Polyakov, 1983 and Vogel and Brandes, 1997).



(1) Upper Mantle (400 km tk.), 1800'F, γ = 3.6-3.9 gm/cm^3 (2) Earth Crust (33km tk.), (3) Outer Core (1000 km tk.), γ =4.7-5.6 gm/cm^3, P = 950 kg/sq.cm , (4) Mohorovici Discontinuity, 0-800'F, γ=2.7-3.6 gm/cm^3, P=100 kg/sq.cm, (5) Lower Mantle (1000 km tk.), 1800'F, γ = 4.5 - 4.7 gm/cm^3 (6) Transition Zone, (7) Inner Core, γ = 8-12 gm/cm^3, P =4000 kg/sq.cm

Fig. 1. Earth Crust and Interior of Earth (After Bott Martin H.P., 1970)

During earthquake tremendous energy is released from the interior of earth in the form of mechanical energy, heat, electrical, nuclear and light energy etc. through these weak points in the earth crust and these locations are called focus or epicenters. Most of the earth quakes have a focus less than or around 33 km, however, in some rare cases they may be as deep as 70 to 200 km.

3 NATURE AND PROPERTIES OF WAVES AND WAVE PROPAGATION

As indicated earlier earthquake energy is released from weak points known as focus or epicenter. This mass-energy propagates through out the body of the earth mass in the form of waves with different velocities, wave length, particle oscillation, direction and amplitude (Polyakav, 1983). The waves travel in all direction. Beyond a certain distance h.tanθ from the epicenter, most of the waves propagate horizontally parallel to the surface of the earth. There are several types of waves and normally the stress displacements we measure may be resultant of several types of waves passing through a given point.

Using seismographs we may be able to separate and identify different types of waves. Significant waves among them are longitudinal waves which are called pressure waves and transverse waves which are called S-waves. P-waves propagate at velocities 2 to 3 times greater than S-waves. The nature of conditions responsible for producing P-waves and S-waves is not clearly understood.

3.1 Properties of Longitudinal Wave - P-waves

Figure 2 schematically shows the propagation of longitudinal or P-waves propagating in an elastic solid media (saturated granular media is described later). In case of P-waves the particles of the transmitting media are displaced along the direction of propagation, giving rise to alternating compressive and tensile strains. At some distance from the source, the divergence of the wave front makes it possible to regard the wave as plane within small portions (Polyakov, 1983). The term plane refers to waves whose propagation on Cartesian co-ordinator may be described by the function.

$S = f\,(t,x)$ .... (1)

The quantity S is independent of y and z. A mechanical model for such a process may consist of a series of elastically connected oscillators one of which (say, the first one) is subjected to a dynamic load acting in the plane of the oscillators. Let the function (1) be represented as S = f (at - bx).

Differentiate twice both with respect to t and x. After simplifying following expression is obtained.

$\frac{\delta^2 f}{\delta t^2} = \left(\frac{a}{b}\right)^2 \frac{\delta^2 f}{\delta x^2} = v_o^2 \frac{\delta^2 f}{\delta x^2}$ wherein v_0 is velocity of propagation of wave.

The expression is $\frac{\delta^2 f}{\delta t^2} - v_o^2 \frac{\delta^2 f}{\delta x^2} = 0$ ...... (2)

This expression (2) is called P - wave equation.

When a longitudinal wave traveling with a velocity v_o passes through a section x and x +Δx as shown in Figure 2, the wave induces stresses σ(x) and σ(x+Δx) and has caused the center of gravity to move through 'u' during oscillation, which may induce a velocity v and strain ε having magnitude varying from zero to maximum. If mass density of the section is ρ and cross sectional area is F, then using Newton's second law following expressions are derived from the relation :

$$\rho\ F\,\Delta x\ \frac{\delta^2 u}{\delta t^2} = F\left[\sigma\left(x+\Delta x\right) - \sigma\ (x)\right];$$

$$\rho\ \frac{\delta^2 u}{\delta t^2} = \frac{\delta \sigma}{\delta x};\ \varepsilon = \frac{\delta u}{\delta x};\ \sigma = E\ .\ \varepsilon;\ v_o = \sqrt{\frac{E}{\rho}};$$

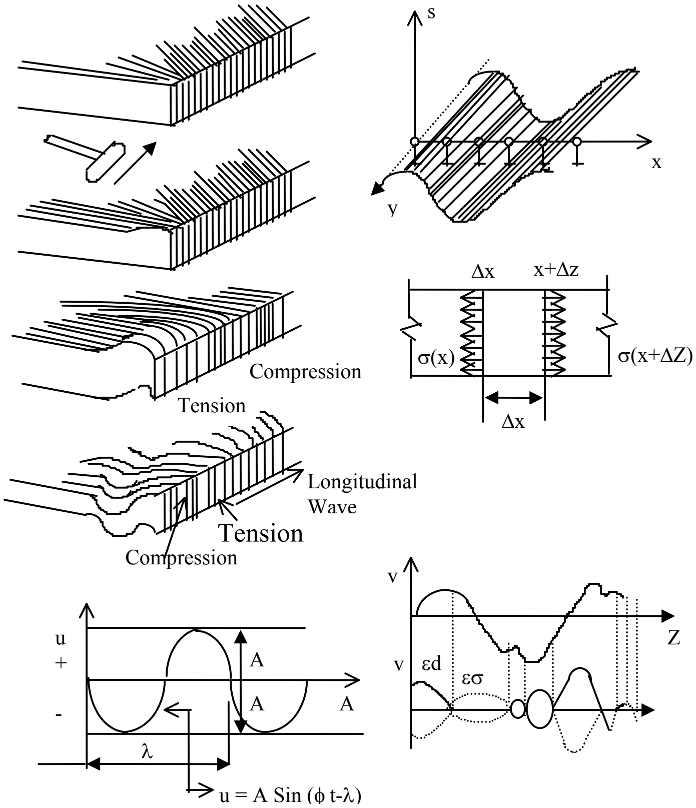


Fig. 2. Wave Propagation (a) Sketch Showing Elastic Media and Direction of Longitudinal Wave

The velocity v of the particle laying in the plane wave coordinate is x = constant, the strain ε and the stress σ are given by taking derivative of the function : $u = f(x \pm v_o)$

$$\mu = \frac{\delta u'}{\delta t}, \ \varepsilon = \frac{\delta u'}{\delta x}, \ \sigma = E \ . \ \frac{\delta u}{\delta x} \text{ and } v = \frac{v_o \sigma}{E}$$

If u is considered as a sine wave propagating then :

$$u = A \sin\left[\frac{2\pi}{\lambda}(v_o t - x)\right] = A \sin(\phi \ t - \lambda)$$

Wherein, λ = wave length ; $v_o = \lambda n$; Where n = frequency ; $\frac{\lambda}{v_o} = \frac{1}{n} = T_w$ = period of vibration .

Thus, by obtaining A, λ, v_o, n from seismograms, one can obtain σ, the stress. This stress will be acting both on pore water and solid particles of saturated granular soil water system, causing excess pore water pressure and volume change. In Figure 3 a typical P-wave seismograph for Richter 7 magnitude of earth quake is shown. From the Figure 3, f = 1.25 cycles/sec. duration 30 seconds and average acceleration 80 cm/sec^2 and maximum 100 cm/sec^2.

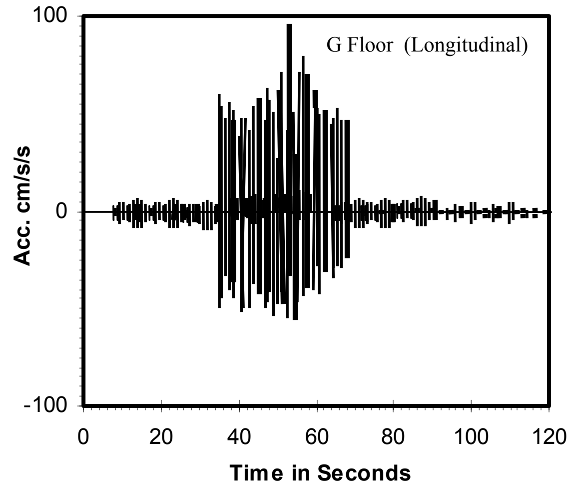


Fig.3. P-wave (Longitudinal) for Richter Around 7, Acceleration vs Time in Seconds.

3.2 <u>Properties of Transverse or Shear Waves</u>

Transverse waves have a velocity much less than longitudinal waves. The velocity may be 1/2 to 1/3 of longitudinal waves. S- waves develop shear stresses in the soil water system and thus they can create displacement of soil particles resulting into volume change which may transfer effective stress into neutral stress. It is possible to model the phenomenon in the laboratory by conducting cyclic shear tests. Bolton Seed and his associates have developed relations to predict initiation of liquefaction in granular media having different SPT-N values and grain sizes under different intensity and period of earth quake. Refer to Seed and Idris, 1971 and Prakash, 1981.

4 **INFLUENCE OF P-WAVES ON EXCESS PORE WATER PRESSURE DEVELOPMENT IN SATURATED SANDY MEDIA**

It is already brought about that mass-energy properties of P-wave while propagating with velocity v_o through an elastic media produce displacement of particle with respect to C.G. while oscillating with amplitude A, frequency f, and wave length λ in the longitudinal direction with velocity of particle μ, and causing strain ε and stress σ in the media.

Saturated sand water system is a two phase system consisting of (1) solid particle skeleton with compressibility, c_{cs} and (2) undrained confined liquid water whose coefficient of compressibility c_w is very low (E is high).

When $\Delta\sigma_{wave}$ stress due to P-wave is acting on the element horizontally as shown in Figure 4, it produces compression of the skeleton and compression of pore water.
According to skempton (Bishop, 1962) such stress conditions produce excess pore water pressure given by the equation.

$$\Delta u = B\left[\Delta \sigma_3 + A\left(\Delta\sigma_1 - \Delta\sigma_3\right)\right]$$

(For more details refer to Bishop and Hankel, 1962 and Terzaghi, 1953).

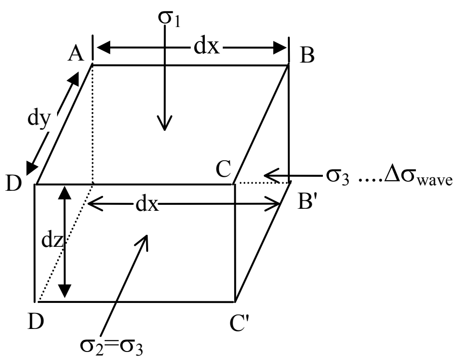


Fig. 4. σ_1 σ_2 σ_3 Total Principle Stress Acting on Sand Water Element Prior to $\Delta\sigma_{wave}$ Acting on it.

In Saturated Sand Media : $\Delta u = \bar{A}\left(\Delta\sigma_1 - \Delta\sigma_3\right)$.

$\Delta\sigma_1$ can be considered as $\Delta\sigma_{wave}$ and the expression can be written as $\Delta u = \bar{A}\left(\Delta\sigma_{wave} - \Delta\sigma_3\right)$. $\bar{A}$ may vary from 0.37 to 0.6.

Cyclic loading depends upon duration and number of cycles N.

$\therefore$Total excess pore water pressure $U = N.\bar{A}\left(\Delta\sigma_{wave} - \Delta\sigma_3\right)$

$\Delta\sigma_3$ may be neglected, $\Delta\sigma_{wave}$ can be obtained by :

$\Delta\sigma_{wave}$ = unit mass x acceleration of element.

Illustrative Example

Let γ_b = 1g/cc, a_{av} = 80cm/sec^2, $\bar{A}$=0.5

$$\Delta\sigma_{wave} = \frac{1}{g} x\ 80\ x\ g = 80 \text{ g/cm}^2$$

Excess Pore Water Pressure per cycle :

$\Delta u = \bar{A}\,\Delta\sigma_{wave} = 0.5x80 = 40 g/cm^2$ or $\Delta u \ t/m^2 = 0.4\ t/m^2$.

Number of cycles in a quake duration 30.

$\therefore$Total built up excess pore water pressure at the end of earthquake shock = 30x0.4 t/m^2 = 12 t/m^2.

Typical values of excess pore water pressure developed for various horizontal acceleration for P wave is given in Table 1.

Table 1. Excess Pore Water Pressure Contributed due to Earthquake of Various Acceleration $\left[\bar{A} = 0.5\right]$

a, as fraction of g	a, cm/sec^2	Δu, t/m^2	Built up excess pore water pressure t/m^2 for various cycle, duration		
			U_{10}, t/m^2	U_{20}, t/m^2	U_{30}, t/m^2
0.05	50	0.25	2.5	5.0	7.5
0.10	100	0.5	5.0	10.0	15.0
0.15	150	0.75	7.5	15.0	22.5
0.20	200	1.0	10.0	20.0	30.0
0.25	250	1.25	12.5	25.0	37.5
0.30	300	1.5	15.0	30.0	45.0
0.35	350	1.75	17.5	35.0	52.5

4.1 Comparison with Observed Excess Pore Water Pressure as Calculated from Height of Jets.

Adani sea port is situated at approximately 70 km from the epicenter of Bhuj earthquake. The port area is having sandy silt deposits. Earthquake intensity at this location was around 6.9 to 7 Richter. Liquefaction depth was around 6 m. Height of jets observed was around 2 m from the ground level, carrying 1 m.m to 2 m.m sand particles. Water Table was around 1 m below G.L, duration 20 seconds with f = 1 HZ. The back calculations showed that excess pore water pressure developed was 13 to 14 t/m^2 and that corresponding to transverse wave as computed was around 6 t/m^2. Thus, remaining 7 to 8 t/m^2 may be attributed to excess pore water pressure contributed by P-wave. This is reasonably comparable to theoretical value observed from Table 1.

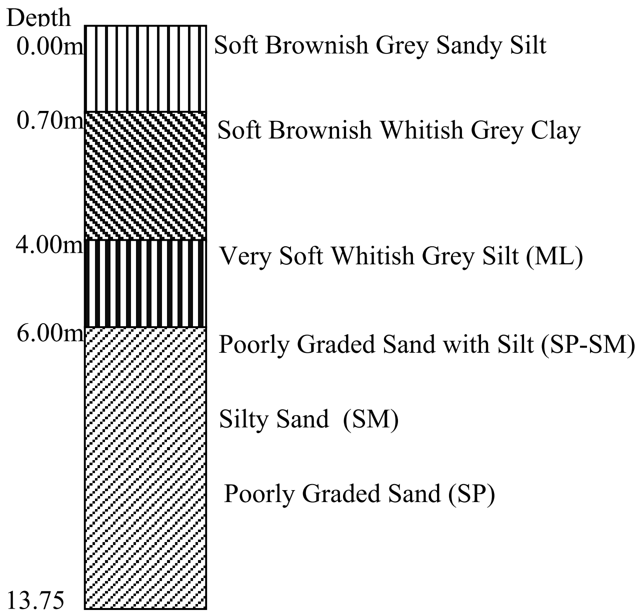
This can also be back calculated by using stokes' law velocity needed for particle of size 1 mm to 2mm to remain in suspension.

5 ENERGY INTERCEPTING BARRIERS

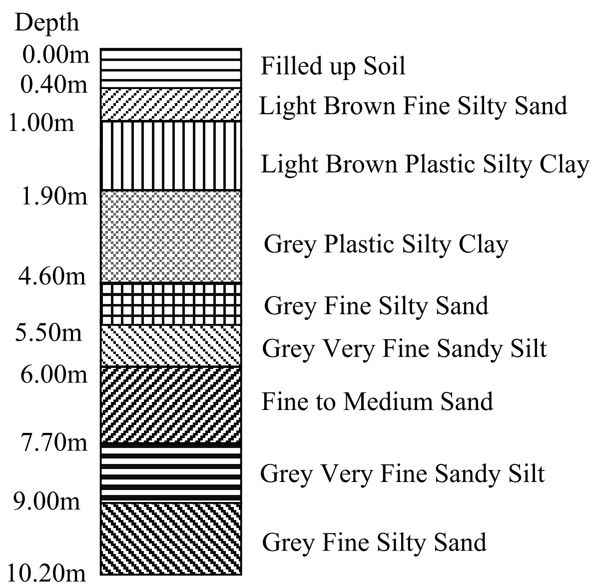
Although energy travels in all direction from the focus, at a distance of h.tanϕ most of the waves travel parallel to the surface of the earth. In other words around 50 to 60% energy travels parallel to the earth surface. The velocity function v_o is equal to $\sqrt{\frac{E}{\rho}}$. Thus, by placing low E value intercepting barrier the velocity of propagation can be reduced considerably. Also the interceptor may play the role of reflection, refraction and absorption of energy waves. E value of steel is 2x10^5 N/m.m^2, wood is 10x10^2 N/m.m^2 and plastic may be 100 N/m.m^2. Geosynthetics may act as a good barrier. By providing the barrier around a big area as a fort or a dam, one may be able to avoid strengthening individual structures to a great extent.

6 REDUCTION IN LOAD CAPACITY OF PILES SUPPORTING RAFT OF STORAGE

In Adani Port complex liquid container tank enclosure is located on the area having silty sand deposits as shown in borehole logs in Fig. 5(a) & (b).



(a) Subsurface Borehole Log (No.L-14) Before Earthquake



(b) Subsurface Borehole Log (No. LT-1) After Earthquake

Fig. 5. Subsurface bore hole logs taken at tank no T-108 prior to and after earthquake

During earth quake this area experienced liquefaction of the surrounding soil. The differential heave between raft and soil was in the neighbourhood of 20 mm to 40 mm. However, no perceptible damage has taken place to substructure.

To understand the loss of strength an attempt is made to compare the SPT-N values with depth taken prior to earth quake and after the earth quake. This is needed for insurance claim.

SPT data is analysed to arrive at relative alteration in strength, in the absence of density, moisture content, shear strength data etc. being made available.

In Fig. 5(a) & (b) borehole log at tank no. T. 108, taken prior to and after the earthquake are shown. This data is provided by Adani Port authorities.

The SPT-N value with depth available from L-14 borehole which was taken prior to earthquake and LT-1 borehole which was taken after earthquake are plotted in Fig. 6. The curve marked (a) is the one showing the state of subsurface prior to earth quake and the curve marked (b) is showing the state of subsurface after the earthquake. It is clear from the Fig. 6 that even on 31st July the SPT values of curve b (LT-1) are much lower than SPT values of curve a (L-14). This shows that the effect of internal disturbances caused by liquefaction continues to persist to varying degrees even on 31/7/2001. From curve (b) it can be said that below 3.0 m, SPT value tends to zero. It can be said that probably change has taken place from solid to suspended particle liquid state.

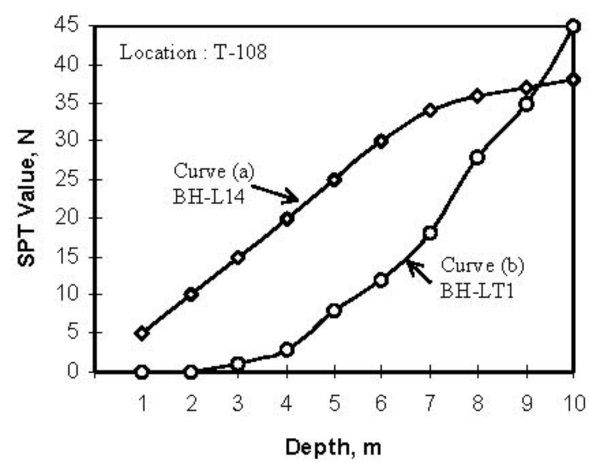


Fig.6. Normalized SPT values, N with depth for (a) BH-L14 prior to earthquake and (b) LT-1 after the earthquake

In Fig. 7 percentage reduction in strength in terms of equivalent reduction in SPT is shown. It may be noted that upto 3.0 m the reduction is 100%. Beyond 3.0 m the reduction reduces from 100% to 50% corresponding to depth of 7.0 m. It may be noted that water table is at a depth of 1.5 m. This means the reduction is 100% to 50% is with respect to buoyant density consideration. Thus this accounts to considerable loss in effective stress. The reduction in strength goes on decreasing upto a depth of 9.3 m. Thus, it can be said that the depth upto 9.3 m is affected by liquefaction / partial liquefaction phenomenon.

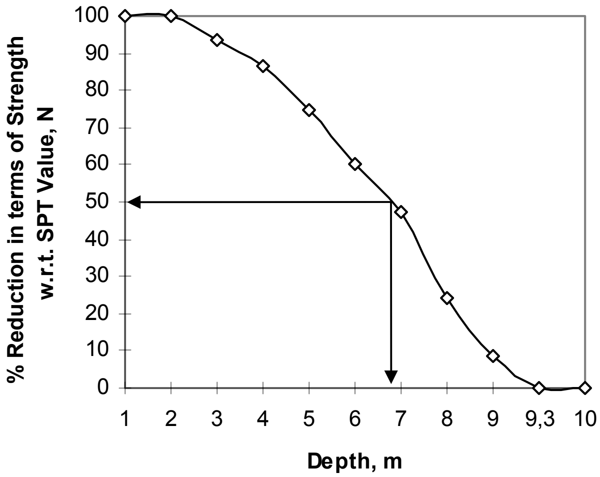


Fig. 7. Plot showing % reduction in sub-surface strength with depth with respect to SPT value, N after earthquake on 26/01/2001 in relation to earlier SPT strength

Thus, with respect to earlier strength, upto 3.0 m almost 100% reduction in strength has taken place and beyond upto 7.0 m around 75% reduction in strength has taken place. Beyond that upto 9.3 m the average 50% reduction has taken place.

It may be noted that during liquefaction / partial liquefaction phenomenon, reduction in strength is caused one by excess pore water pressure and second by dilatancy effect. Both these aspects seem to be contributing to reduction in strength of soil and contributing to reduction in strength of pile foundation. The shear strength parameters tan ϕ_1 prior to earthquake and tan ϕ_2 after earthquake with respect to depth are given in Table 2 and Fig. 8.

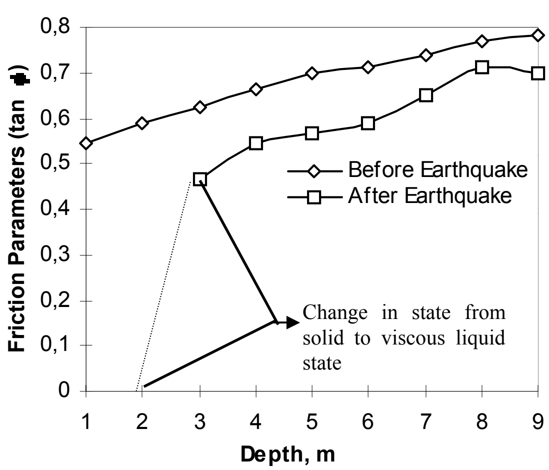


Fig. 8. Plot showing friction parameter (tan ϕ) with depth (before and after earthquake)

It may be noted that upto around 3.0 m the state of soil has completely changed and it appears to be loosely structured soil water system. Thus, this shows that the original structure is completely destroyed and new structure is getting formed in the soil water system. From this it can be concluded that there is also a change in friction parameters (tan ϕ_1) due to combined effect of excess pore water pressure and dilatancy. In addition it is already brought out that there is a reduction in effective stress due to increase in excess pore water pressure.

Table 2. Values of tan ϕ prior to and after earth quake

Depth (m)	tan ϕ_1 (τ/σ) prior to earthquake	tan ϕ_2 (τ/σ) after earthquake
1.0	0.5429	0.0
2.0	0.5890	0.0
3.0	0.6248	0.4663
4.0	0.6619	0.5429
5.0	0.7002	0.5658
6.0	0.7133	0.5890
7.0	0.7399	0.6494
8.0	0.7673	0.7133
9.0	0.7813	0.7002

Allowable bearing capacities are estimated based on SPT values prior to and after earthquake. It is observed that reduction in allowable bearing capacity upto a depth of 3 m is almost 100% and beyond that the reduction reduces and it is 50% at depth of 7m. At a depth of 9.3m the reduction becomes zero.

7 SUMMARY AND CONCLUSIONS

In summary, earthquake is caused by various types of energies generated from various types of matter present in the interior of the earth and released from certain weak points in the earth crust called focus and epicenter.

The energy propagates in all directions from focus in a wave form. Different types of energies propagate with different velocity, amplitude, wave length and frequency. Predominant among them are P-waves and S-waves.

Thus, predictions and field realities may match more closer, if quantum or wave mechanics relations are used coupled with Newtonian mechanics relations for vibration of granular particles and for civil engineering structures founded on them.

Although the waves propagate from the focus in all direction in a spherical mode, because of sphericity of earth crust, at a short distance away from the focus the waves predominantly propagate in a horizontal direction parallel to the earth surface.

Velocity of propagation of energy is a direct function of root of modulus of elasticity E and inverse function of mass density ρ. With distance from the focus the intensity of earthquake energy attenuates due to loss of dissipation during propagation. The above properties and earthquake as a flow of energy, it may be possible to reduce impact of earthquake energy by intercepting the flow with earthquake intercepting barriers around a large area as a fort. These barriers may reflect, refract and absorb earthquake energy and thus, reduce impact of earthquake on structures inside the barriers. Thus, individual structures will be less affected.

Excess pore water pressure contribution of P-waves, based on wave equation coupled with skempton's $\bar{A}$ and B parameters analysis shows that theoretical analysis and field observations reasonably match. Although pile-raft foundations appear to have undergone less displacements and visibly less damaged during liquefaction during earthquake, the SPT-N value tests conducted prior to and after earthquake in the surrounding soil show considerable reduction in pile load strength, needing strengthening.

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